IMPROVED ACCURACIES FOR SATELLITE TRACKING

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ABSTRACT

A CCD camera on an optical telescope which follows the stars can be used to provide high accuracy comparisons between the line of sight to a satellite, over a large range of satellite altitudes, and lines of sight to nearby stars. The CCD camera can be rotated so the motion of the satellite is down columns of the CCD chip, and charge can be moved from row to row of the chip at a rate which matches the motion of the optical image of the satellite across the chip. Measurement of satellite and star images, together with accurate timing of charge motion, provides accurate comparisons of lines of sight. Given lines of sight to stars near the satellite, the satellite line of sight may be determined. Initial experiments with this technique, using an 18 cm telescope, have produced TDRS-4 observations which have an rms error of 0.5 arc second, 100 m at synchronous altitude.

Use of a mosaic of CCD chips, each having its own rate of charge motion, in the focal plane of a telescope would allow point images of a geosynchronous satellite and of stars to be formed simultaneously in the same telescope. The line of sight of such a satellite could be measured relative to nearby star lines of sight with an accuracy of approximately 0.03 arc second. Development of a star catalog with 0.04 arc second rms accuracy and perhaps ten stars per square degree would allow determination of satellite lines of sight with 0.05 arc second rms absolute accuracy, corresponding to 10 m at synchronous altitude.

Multiple station time transfers through a communications satellite can provide accurate distances from the satellite to the ground stations. Such observations can, if calibrated for delays, determine satellite orbits to an accuracy approaching 10 m rms.

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INTRODUCTION

The U.S. Naval Observatory, as part of its primary mission, makes accurate astrometric observations of stars and solar system objects, maintains the Master Clock of the United States, and makes precise time comparisons between that clock and other time standards around the world. As a by-product of these activities, techniques for improved satellite tracking have been developed.

Charge coupled device (CCD) chips are light sensitive integrated circuits used in astronomy for photometric and astrometric observations. Some of the characteristics applicable to artificial satellite observations with a telescope guided to follow the stars are that

1) high quantum efficiency permits short exposure times,
2) pixel and image sizes permit accurate determination of the centroid of the image,
3) variable read-out rates permit accumulating into pointlike charge images photoelectrons from a satellite optical image moving across the chip as well as from star images fixed on the chip,
4) observations can be read directly from chip to computer for immediate, automated analysis, and
5) mosaics of CCD's can be operated so that one CCD tracks a satellite and others accumulate star images, allowing relative positions to be determined accurately.

The characteristics of the CCD detector mean that a relatively small telescope, of 20-50 centimeter aperture, can be used. The trade-off between field of view, duration of observation, and accuracy of observation is dependent upon the size of the CCD or mosaic, the size of the pixels, and the telescope specifications. Depending on the operational requirements, specific instrument designs and observational procedures can be implemented. With computer control, the entire process of obtaining images and extracting from them satellite line of sight information can be performed autonomously.

Equipment used for time transfer through communications satellites allows measuring accurate ranges from ground stations to a communications satellite. High accuracy orbits can be determined from the range data. Calibration of range biases can be accomplished by high accuracy optical observations.

OBSERVATIONS OF TDRS-4

Observations are made with a Photometrics series 200 CCD camera containing a 1024 by 1024 Thompson CCD chip which has a photosensitive area 2 centimeters on a side. Each pixel of the CCD covers a region of the sky 2.4 seconds of arc on a side, and the CCD chip covers a region 40 arc minutes on a side. The CCD camera is attached by a rotator to a 18-cm-aperture telescope of 168-cm focal length, guided to follow the stars. The rotator allows aligning the columns of the CCD chip with the direction of satellite motion relative to the stars. By controlling the rate of motion of charge along columns of the CCD chip, it is then possible to accumulate photoelectrons from the satellite image.

Observation times and fields are chosen so that the satellite observed, TDRS-4, will be in the same field with two reference stars in a star catalog. The telescope is pointed to the direction of the center of the desired field and the CCD camera is rotated so that the satellite image moves along CCD columns. When the satellite is near the center of the field, the shutter is opened and the CCD controller advances charge from row to row of the CCD at a rate matching the motion of the satellite. This charge transfer is identical to the charge transfer normally accomplished when reading out the CCD chip after an exposure, but is commanded row by row by a specially designed timing circuit. This circuit causes a uniformly spaced sequence of charge advances and allows the times of charge advance to be accurately determined.

After a pre-fixed number of rows is transferred (40 in the present case), depending on the brightness and thus the required exposure time of the satellite (6 seconds in the present case), charge transfer stops and the shutter is closed for a few seconds. At the end of charge transfer, the charge image of the satellite extends over only a few pixels while star images are trails 40 rows long (Figure 1a).

The shutter next opens, for a star exposure with no charge motion, to form the charge image found in Figure 1b. While the shutter is closed before this exposure, there is an interval of charge advance and there is an interval in which charge does not move but the satellite optical image continues its motion downward in the figure. The shutter last opens for a star exposure which forms the charge image shown in Figure 1c. There is again before this exposure an interval of charge advance and an interval with no charge motion. The durations of the star exposures are 2 seconds, sufficient to allow accurate measurement of the centroids of the star images. After the shutter closes for the last time, charge is read out of the CCD chip.

MEASUREMENT OF IMAGES

The satellite charge image at the end of the satellite exposure is the sum of the charge images produced in the intervals between charge advances. The centroid of the distribution, at the end of the satellite exposure, of the photoelectrons produced in a particular interval is the centroid of the optical image of the satellite at the middle of the interval, advanced by an integer number of rows. The centroid of the final satellite charge image is thus the centroid of the optical image of the satellite at the midpoint of the satellite exposure, advanced by the average of the amounts by which the summed images are advanced.

Observed CCD frames are analyzed with an interactive image processing program which displays a CCD frame on a screen and allows adjustment of brightness and contrast for maximum visibility of star and satellite images. Using a mouse-controlled arrow displayed on the screen, the user indicates the point image of the satellite and the two point images of each reference star. The program locates the brightest pixel near each indicated position and forms a smaller, 7-by-7 subimage centered on this brightest pixel. From each pixel brightness in the subimage is subtracted the average of the brightnesses of all pixels in the subimage. The center of the subimage is calculated to be the centroid of the pixels with positive differences, each such pixel weighted by its difference value.

The determined satellite position for a CCD frame corresponds to the position, with respect to the midpoint of the great circle arc connecting the reference stars, of the satellite at the observation time. Displacement components are measured in pixels in the direction of satellite motion and in an orthogonal direction. The distance in pixels between the reference star images is also measured.

COMPARISON OF MEASURED POSITIONS TO DETERMINED ORBITS

Following each night of optical observations of TDRS-4, Goddard Space Flight Center provides satellite positions and velocities at two-hour intervals from an orbit fit to a span, including the time of the optical observations, of radio data. A numerical orbit integrator is used to calculate the position of the satellite at the time of each satellite observation.

An observation simulation program calculates the observed lines of sight of the two reference stars for each CCD frame, and the distance between them, on the basis of positions in the star catalog. Simulated lines of sight are calculated by applying refraction to apparent places which include proper motion, precession, nutation, and that part of aberration due to the motion of the center of mass of the Earth.

Together with the reference star lines of sight, the observation simulation program calculates for each frame the line of sight to the satellite at the observation time. The satellite line of sight includes the effects of refraction, the motion of the satellite in the light time to the observer, polar motion, and the difference between UT1 and UTC. The satellite orbit as provided by Goddard Space Flight Center is with respect to true of date coordinates with the FK4 equinox, while Earth orientation and star positions are given with respect to true of date coordinates with the FK5 equinox. To convert satellite positions to true of date coordinates with the FK5 equinox, the satellite is displaced forward 0.070 second of time in its orbit.

From the lines of sight are calculated the components, in the direction of satellite motion and an orthogonal direction, of the displacement to the satellite line of sight from the midpoint of the great circle arc connecting the reference star lines of sight. That part of aberration due to the rotation of the Earth is included neither in the simulated star nor satellite lines of sight.

The observation simulation program calculates all distances in radians and converts these values to pixels, using an angular pixel size which is constant for a night's observations. The simulation program is run once to determine the angular size of a pixel (the scale of the frame) by comparing the observed sum of distances between reference stars with the sum calculated using an assumed pixel size. A second run of the simulation program uses the angular pixel size calculated in the first run.

We consider the measured position of each image to be the sum of a random position measurement error and a measured image position averaged over all possible variations in atmospheric refraction and over all possible image measurement errors. We further consider that the line of sight of each reference star, calculated from its catalog position and a mean refraction value, differs from the line of sight corresponding to the mean image position by a catalog error with zero mean.

Figure 2 shows, for CCD frames made in observing sessions near 0 hours UT on December 10, 11, and 13, the deviations of measured from calculated distances between reference stars. Each deviation is the sum of the position measurement error and the catalog error along the great circle connecting the stars. The root mean square value of the deviations is 0.49 arc second.

The star catalog used is the Astrographic Catalog Reference System (ACRS) catalog developed at the U.S. Naval Observatory by Corbin and Urban (1990) to provide the most accurate high-density reference catalog (325,000 stars) available. The standard deviation in each coordinate is 0.21 arc second for 1990. This error contributes 0.30 arc second to the root mean square difference of calculated and measured distances between two reference stars. Differences of refraction with star color add a further error, since no filter is used in the optical system. Errors in the distance due to variations in atmospheric refraction and those introduced in the process of recording and measuring star images must together have approximately 0.38 arc second standard deviation in order for the sum of the square of this standard deviation and the square of the standard deviation of catalog error to reach the observed (0.49 arc second)2. Dividing by the square root of 2 gives the value 0.27 arc second, or 0.12 pixel, for the standard deviation of each component of the position measurement error.

Figure 3 shows the displacement of measured from calculated TDRS-4 lines of sight on three nights in December 1990. Different reference stars are used for each observation. The rms value, for all observations on the night of December 10, of the displacement of the measured from the calculated satellite line of sight is 0.25 arc seconds; corresponding values for December 11 and 13 are 0.58 and 0.55 arc second. An angular displacement of 0.5 arc second, 0.21 pixel, corresponds to a linear displacement of 100 meters at synchronous altitude. The mean displacement of measured from calculated lines of sight is within 0.5 arc second of a constant one arc second westward offset for each night. Changes from night to night in the mean displacement are consistent with the accuracy stated for the provided satellite ephemerides. The cause of the one arc second offset is not at present understood. Possible causes of the offset include software errors and misunderstanding of the coordinate system used for the provided orbit.

We also reduced the data using the Smithsonian Astrophysical Observatory (SAO) star catalog. As expected from the known errors in this catalog, rms deviations of measured from calculated satellite lines of sight were twice as large as those in lines of sight measured by comparison with the ACRS catalog stars. The improvement produced by using the ACRS catalog rather than the SAO star catalog points out the importance of using the most accurate star catalog available and the need for high-density star catalogs considerably more accurate than ACRS.

HIGH ACCURACY SATELLITE LINE OF SIGHT DETERMINATION BY OPTICAL OBSERVATIONS

An instrument for high accuracy optical satellite observations might consist (Kammeyer, Fliegel, and Harrington, 1990) of a 0.5-meter aperture telescope of 4-meter focal length with a 2000 by 2000 pixel CCD focal plane assembly having 20 micron pixels (Figure 4). The focal plane assembly could be either a single, specially designed CCD chip, or a mosaic of CCD chips. When observing a satellite, part of the focal plane assembly would form point images of stars and part would form a point image of the satellite (Figure 5). The time required for the optical image of a geosynchronous satellite to cross the focal plane assembly, which corresponds to a 30 by 30 arc minute region of sky, is two minutes. A narrow bandpass filter is shown, which reduces the number of photoelectrons to 8000 per pixel for an image of 3 pixel radius, exposed 40 seconds, of a magnitude 10 star (filter transmission is 50% and CCD efficiency is 40%). Such a narrow bandpass makes refraction differences with color insignificant.

By making several exposures in the crossing time of a geostationary satellite, the line of sight to such a satellite could be located to perhaps 0.03 arc second rms relative to nearby stars. This includes a one-fortieth pixel error due to causes within the CCD (Monet, 1988) and an error of 0.01 arc second due to atmospheric turbulence (Han, 1989). If several stars in the field of the telescope had lines of sight known to an absolute accuracy of 0.04 arc second rms, the line of sight of the satellite could be determined with an absolute accuracy of 0.05 arc second, corresponding to 10 meters at synchronous altitude.

The ideal source of star positions would be a star catalog with 0.04 arc second rms accuracy and approximately ten stars per square degree. An alternative approach, too expensive to apply to more than a small number of ground stations and geostationary satellites, would be to measure relative star positions in small regions along the observed paths of the satellites. Calibration with the U.S. Naval Observatory optical interferometer could be used to convert the relative measurements of star positions in each region to absolute star positions. The optical interferometer will be able to measure star positions with an accuracy better than 0.01 arc second.

Another technique for determining an absolute line of sight for a satellite would not require the use of absolute star positions. In this technique, one would observe passages of a Global Positioning System (GPS) satellite and of the geostationary satellite through the same star field. The rms error in locating the line of sight of a GPS satellite relative to nearby stars with the described instrument is expected to be approximately 0.04 arc second (Kammeyer, et al., 1990). This includes a one-fortieth pixel error due to causes within the CCD (Monet, 1988) and an error of 0.025 arc second due to atmospheric turbulence (Han, 1989). Excluding error in the GPS ephemeris, the line of sight of the geostationary satellite near its crossing of the path of the GPS satellite could be determined to an accuracy of 0.05 arc second. GPS ephemeris error, approximately 0.025 arc second (2.5 meters) for a GPS definitive orbit at present, raises the line of sight error to 0.06 arc second.

SATELLITE TRACKING USING TIME TRANSFER TECHNIQUES

Time transfer at the nanosecond level between widely separated radio transmitters using communications satellites is a new technique currently in its experimental stages. It uses spread spectrum coding techniques developed by Hartl et. al. (1983, 1985). The experiments are being currently conducted by the U.S. Naval Observatory, in collaboration with National Institute of Standards and Technology in Boulder and National Research Council in Ottawa. The experiments involve the SBS-3 communications satellite and ground stations in Washington, DC, Boulder, CO, Ottawa, ONT, and Miami, FL.

This technique has also been used for range measurements from one station. These measurements demonstrate an rms scatter of 1 nanosecond in round-trip time, corresponding to 30 cm in round-trip distance, over 5 minutes (W. Klepczynski, USNO, private communication).

Microwave transmissions are subject to many influences: atmospheric effects, placement of equipment at the ground station, orientation of the spacecraft, etc. However, transmission is independent of clouds and daylight, and the other effects can be brought down to less than 30 cm rms in range. The combined effect of all error sources is to produce a satellite to ground station range error less than 40 cm rms.

By using simultaneous ranging from three ground stations, the position of the satellite can be determined uniquely through triangulation. For three ground stations spread over approximately 2000 km north-south and east-west, 40 cm range errors will produce errors in satellite position of approximately 10 m rms.

Ranging measurements with this technique are limited to communications satellites. However, ground stations installed for time transfer purposes could be used intermittently for tracking. The stations should be selected or established with the widest possible separation in both east-west and north-south coordinates. If optical calibration observations were also applied, then a tracking operation might be inexpensively conducted with 10 m - 20 m rms error.

References

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Monet, D.G.: 1988, in *Ann. Rev. Astron. Astrophys.* **26**, 413

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(a) CHARGE MOTION — CCD CHIP AFTER SATELLITE EXPOSURE — SATELLITE IMAGE, STAR IMAGE

(b) CHARGE MOTION — CCD CHIP AFTER FIRST STAR EXPOSURE — SATELLITE IMAGE, STAR IMAGE

(c) CHARGE MOTION — CCD CHIP AFTER SECOND STAR EXPOSURE — SATELLITE IMAGE, STAR IMAGE
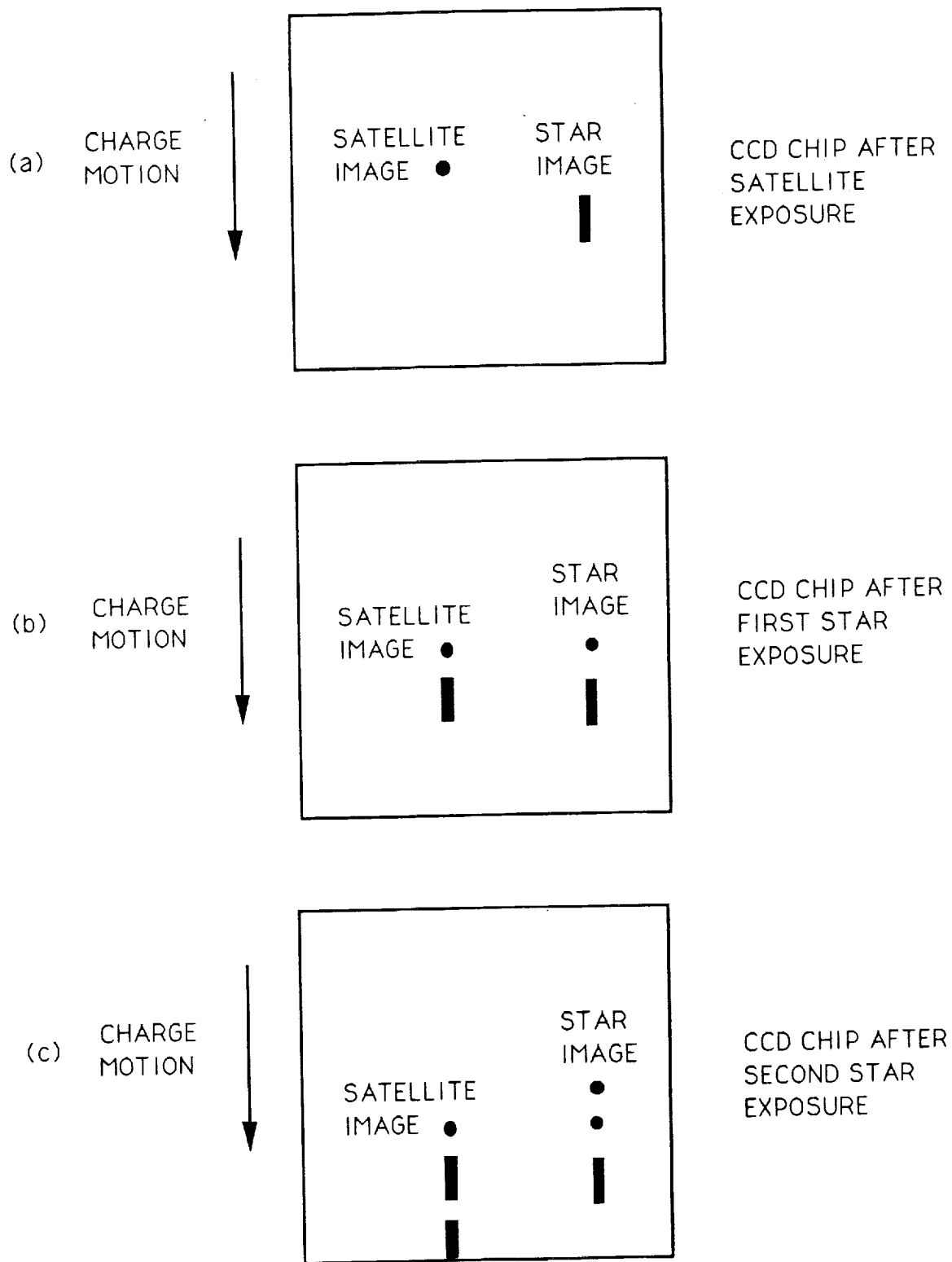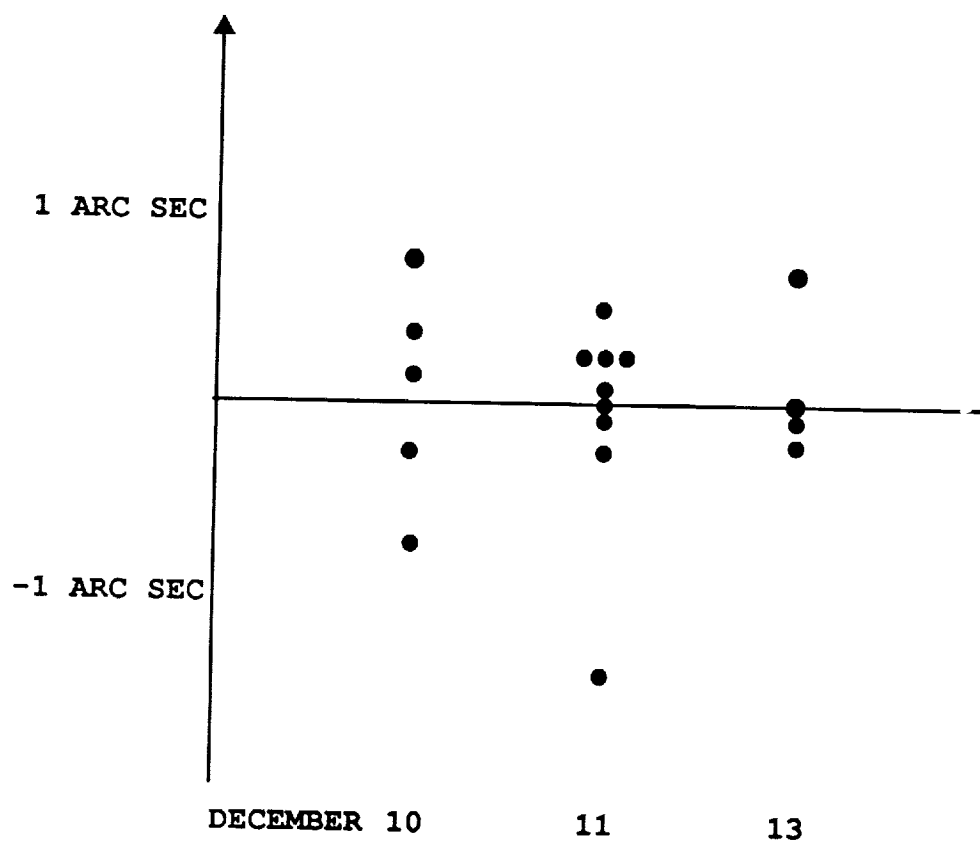
FIGURE 1. FORMATION OF SATELLITE AND STAR CHARGE IMAGES

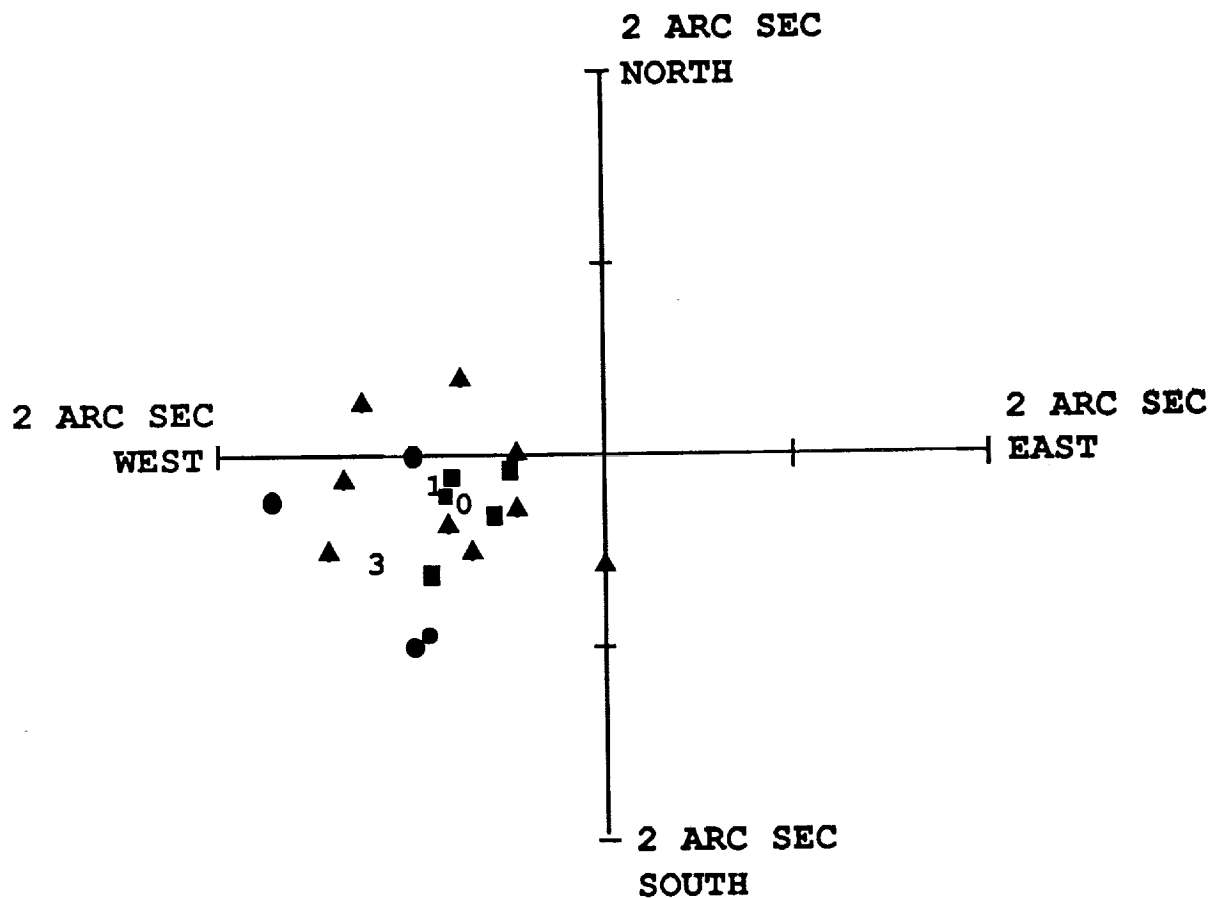FIGURE 2. DEVIATIONS FROM CALCULATED TO MEASURED
DISTANCES BETWEEN REFERENCE STARS

FIGURE 3. TDRS D RESIDUALS(OBS-CALC) ON
- DECEMBER 10, 1990
▲ DECEMBER 11, 1990
● DECEMBER 13, 1990

0,1,3 MARKS MEAN RESIDUAL FOR
DECEMBER 10,11,13

FROM 0.5 METER f/8 TELESCOPE

200 Angstrom Filter

FOCAL PLANE ASSEMBLY--
2000 BY 2000 CCD CHIP,
HALVES INDEPENDENTLY
   CONTROLLED
1 PIXEL = 1 ARC SECOND

DIRECTION
OF CHARGE
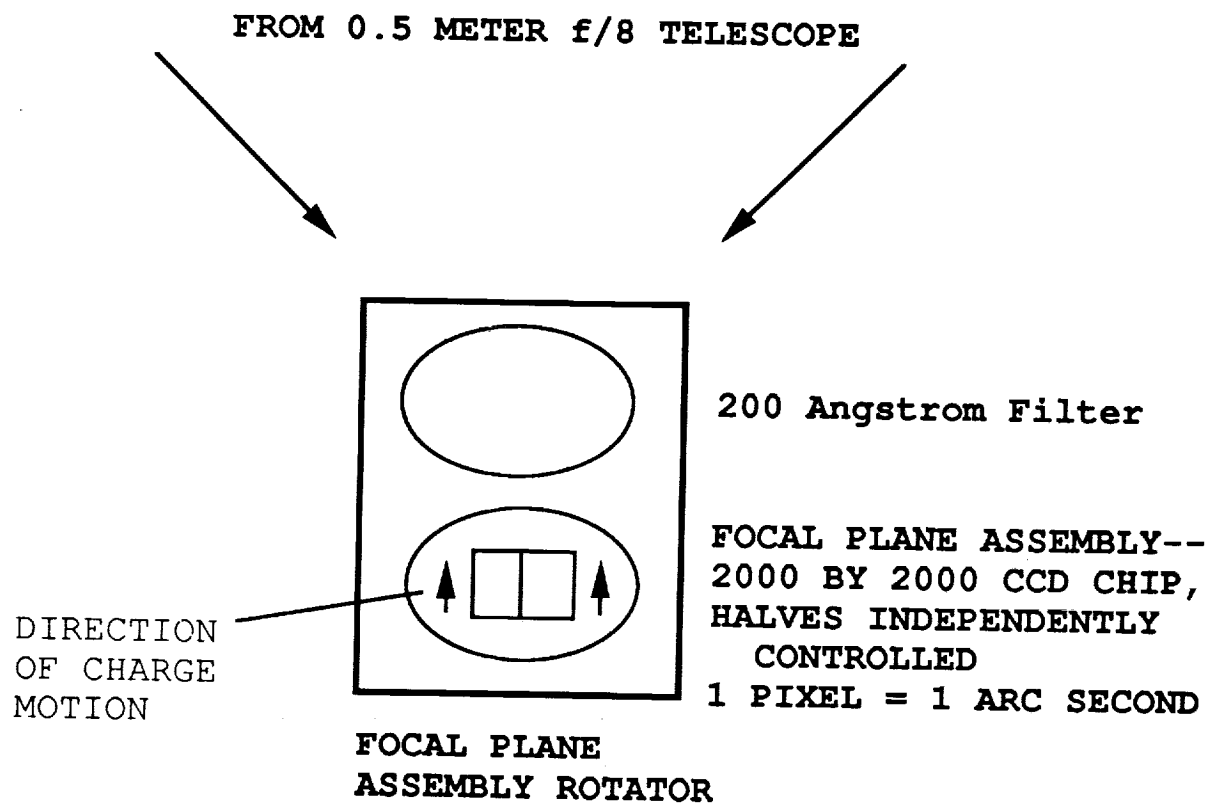MOTION

FOCAL PLANE
ASSEMBLY ROTATOR

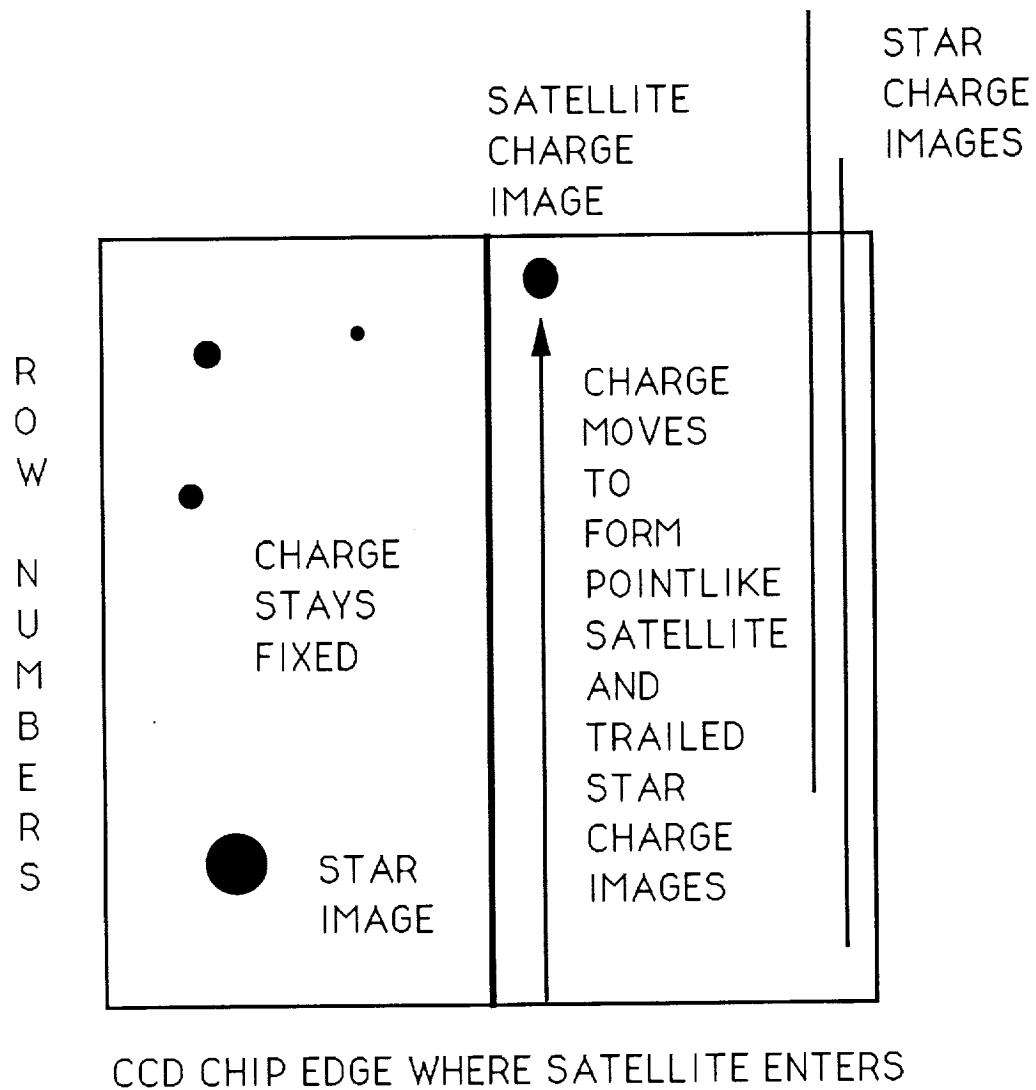Figure 4. Focal Plane Assembly of Satellite Telescope

Figure 5. Operation of Focal Plane Assembly

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